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# THREE-DIMENSIONAL MODELING OF BASIN AND RANGE GEOTHERMAL SYSTEMS USING TOUGH2-EOS1SC

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## ABSTRACT

The Basin and Range (B&R) province is host to numerous geothermal systems with observed temperatures of 200–280°C at 2–3 km depth. Most of these were blind discoveries and are poorly understood. No known magmatic heat source for these exist; rather deep circulation of meteoric water through structural conduits in the presence of steep conductive geothermal gradients is believed to drive these systems. B&R systems are geologically transient—triggered by recent and ongoing tectonic events.

Using TOUGH2-EOS1sc, we investigated a three dimensional (40×26×12 km) polygonal model of an idealized B&R system. Various combinations of bulk rock and range-front fault permeability were tested with the fault zone extending down to 8 km depth. A basal heat flow of 85 mW/m$^2$ was used for all models.

Two end-member conceptual models for this setting were considered, both terminating in a narrow tube-like conduit for upflow within the range-front fault plane. Concept 1 supplies fluids into this conduit at depth from a deep, distributed source. Concept 2 adds significant horizontal flow within the fault plane, supplying the bulk of upflowing fluids. A spectrum of combinations for these two end members was also evaluated. TOUGH2 models of these concepts were calibrated to observations at Dixie Valley, NV.

The upflow zone for Concept 1 was modeled as a narrow, vertical conduit (~1 km×200 m) along the fault plane with permeability k = $10^{-14}$ m$^2$. Various permeabilities of bulk rock were tested. Models with deep basin (bulk rock) k > $5\times10^{-17}$m$^2$ exhibited upflow through the conduit, reaching a thermal peak in 50–300 ka). Deep inflow of cooler water below the basin eventually cools these systems. Models with bulk rock k < $5\times10^{-17}$ m$^2$ required millions of years to reach maximum thermal outflow, with no apparent falloff of outflow temperature.

Models of Concept 2 maintained the narrow conduit in the fault ($10^{-14}$ m$^2$), assumed low bulk rock permeability (< $5\times10^{-17}$ m$^2$), but allowed convection in the entire fault plane (extending 26 km horizontally, k= $10^{-16}$ m$^2$). Initial pressure was hydrostatic, with temperature either set by conductive gradient or with the fault plane preheated by earlier circulation of fluids. Results from all of these models show extensive fluid flow along the fault plane to the narrow conduit. Also, cooling of the bulk rock does not occur after a thermal maximum is reached. Models with a preheated fault plane reach higher temperatures much more quickly (100–500 ka).

Concept 1 and Concept 2 models were then tested using k = $10^{-13}$ m$^2$ in the fault conduit and $10^{-17}$ m$^2$ in the bulk rock. All of these models showed a thermal "pulse" in 500–1500 years. The pre-heated high-permeability conduit model showed significantly higher temperatures than all other models (295°C at 3 km depth).

Bulk rock permeabilities > $5\times10^{-17}$ m$^2$ at depths >8 km are probably not found in actual B&R systems. B&R geothermal systems also appear transient, reaching temperature maximums in <100 ka, and do not appear to cool the deep basin. Adding the third dimension of fluid flow along a "preheated" fault plane and increasing the permeability of the fault conduit may help to explain the geologic, temporal, and thermal evolutions of these systems.

## INTRODUCTION

Non-magmatic B&R geothermal systems present many vexing questions. Most importantly, how does the system achieve very high temperature fluids at relatively shallow depth. Blackwell et al. (2000) reports temperatures in excess of 280°C at 3 km depth in Dixie Valley.

Dating of sinter deposits and springs in Dixie Valley indicate that "episodic" geothermal activity may be temporally related to seismic events (Lutz et al., 2002). These events are relatively recent (<6 ka) with possible associated sinter deposits dating to within a few hundred years of the initiation of these events.

The sources of fluids in these systems is also of interest. Helium isotope studies indicate that a portion (~7.5%) of the helium in these systems is derived from the mantle, and that there is a mixing trend with other meteoric waters (Kennedy and Soest, 2006).

Previous modeling efforts have investigated the effects of topographically driven flow in mountainous terrain (Forster and Smith, 1989), demonstrating that fluid pathways from topographic highs are driven to greater depths than low-relief terrains, with advective heat transport as fluids ascend along fractures. Looking specifically at B&R terrains, McKenna (2004) expanded on this study with a 2D model extending to 8 km depth with upflow along range-bounding faults to look at the effect of rock permeability on transient heating processes. These models reached temperatures close to those observed in Dixie Valley, but required assumptions of bulk rock permeability, and the temporal response of these models are inconsistent with field data. López and Smith (1995, 1996) utilized 3D models (3 km depth) to investigate fluid flow within a fault "plane" in a thermally convective system (as seen in the B&R), demonstrating the effect of anisotropic permeability on flow patterns in the fault plane. Their models did not reach temperatures seen in Dixie Valley geothermal systems.

This study expands on the work done by McKenna, using a 3D model to 12 km depth. The fault geometry contains a narrow vertical "conduit" for fluid flow, along a range-bounding fault "plane." Increasing the permeability along the fault plane is also investigated.

## MODEL

A 3D polygonal model consisting of 7740 nodes (and 23,652 connections) was created to represent a typical B&R "block," approximately 40×26×12 km (Fig. 1b). Distribution of lithologies is illustrated in a cross section perpendicular to the fault (Fig. 1a). These lithologies extend the full width of the model along fault strike, except for "fault conduit" and "fault transition."

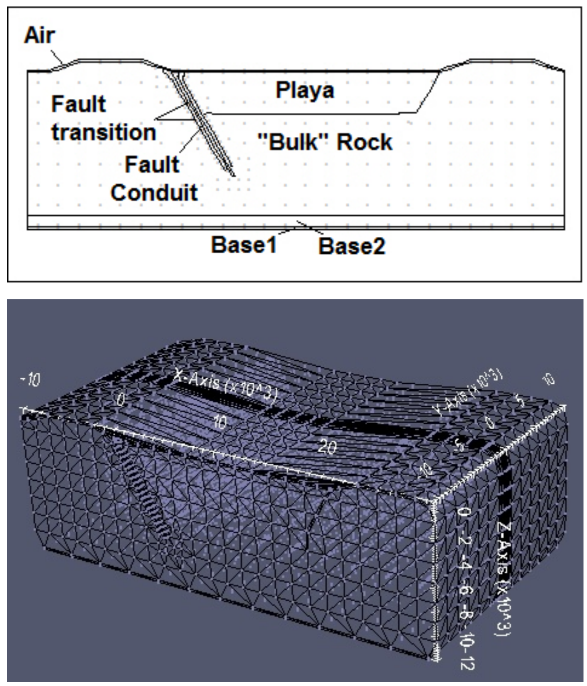



Figure 1. (a) x-z Cross section through the center of the model with rock type blocks noted; (b) 3-dimensional polygonal mesh replicating the x-z section in the y direction.

The fault conduit is 5 cells wide within the fault play, with a single column of cells on either side as a fault transition or "skin" (Figs 2a –b). Rock properties assigned to elements within blocks are shown in Table 1.

Models were run until passing a temperature maximum along the fault conduit. Results for node points located at 3 km depth (equivalent to the deepest observation point at Dixie Valley) and at the bottom of the conduit were monitored for calibration. Fluid transport properties (heat capacity, expansivity, viscosity) were also monitored to evaluate their role in supporting these surprisingly vigorous B&R geothermal systems.

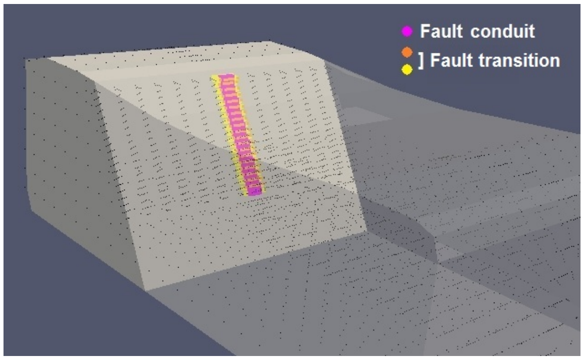



Figure 2a. Fault conduit and transition elements used for Concept 1 models.

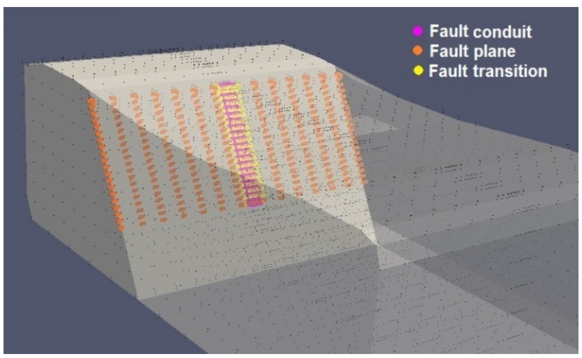



Figure 2b. Fault conduit, transition and fault plane elements used for Concept 2 models.

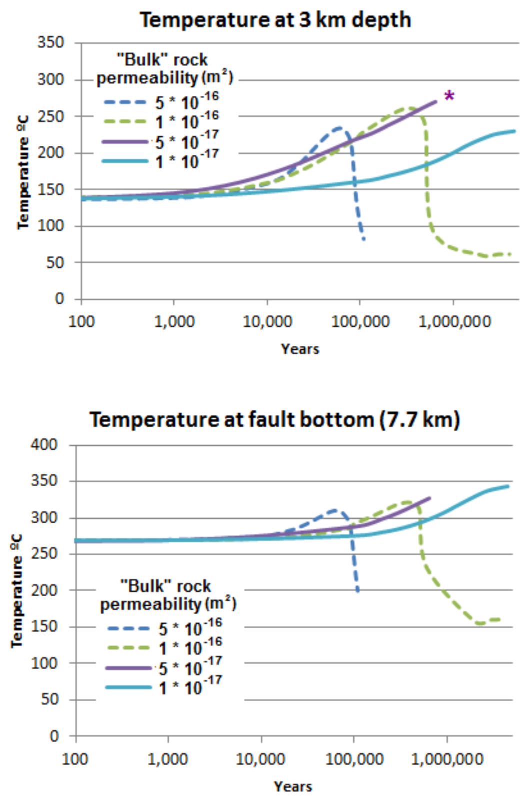
Table 1. Rock Properties

| Block | | Permeability | Conductivity ($Wm^{-1}K^{-1}$) |
|---|---|---|---|
| Bulk Rk. | Concept 1 | $5 * 10^{-16}$ to $1 * 10^{-17}$ $m^2$ | 2.5 |
| | Concept 2 | $1 * 10^{-17}$ $m^2$ | 2.5 |
| Conduit | Concepts 1 and 2 | $1 * 10^{-14}$ $m^2$<br>*$1 * 10^{-13}$ $m^2$* | 2.5 |
| Flt. transition | | $1 * 10^{-15}$ $m^2$ | 2.5 |
| Fault plane (concept 2) | | $1 * 10^{-16}$ $m^2$ | 2.5 |
| Playa | | Horiz.: same as bulk<br>Vert.: $1 * 10^{-19}$ $m^2$ | 1.25 |
| Base 1 | | 1 * 10-20 $m^2$ | 2.5 |
| Base 2 | | 1 * 10-18 $m^2$ | 2.5 |

## RESULTS

### Results for Concept 1 models

Figures 3a and 3b are plots of temperatures at 3 km depth and at the bottom of the fault conduit over time for a range of bulk rock permeability.




Figures 3a, 3b. Temperatures in fault conduit at (a) 3 km and (b) temperatures at bottom of fault conduit for Concept 1 models. * Flow "bottlenecks" within the fault conduit cause models with bulk rock permeability = $5 * 10^{-17}$ $m^2$ to slow at ~620 ka.

For bulk permeability of $5 \times 10^{-16}$ and $1 \times 10^{-16}$ $m^2$, a temperature maxima of 234°C and 261°C is reached at 60 ka and 300 ka (respectively) at 3 km depth, after which the entire model block cools due to convection. The progression of this model (Figure 4) is not realistic for actual B&R systems.

Models with bulk permeability $10^{-17}$ $m^2$ heat to a temperature "maximum" of 230°C at 4.5 ma (Figure 5), at which point the model reaches steady-state equilibrium and converges. This is also not realistic for B&R systems.

Models with bulk rock permeability of $5\times10^{-17}$ $m^2$ heat to 270°C in ~620 ka, after which the model computationally slows appreciably because of “bottlenecks” in the flow “into” the fault conduit (from the top of the fault). Because of this, these models were not run past 650 ka.

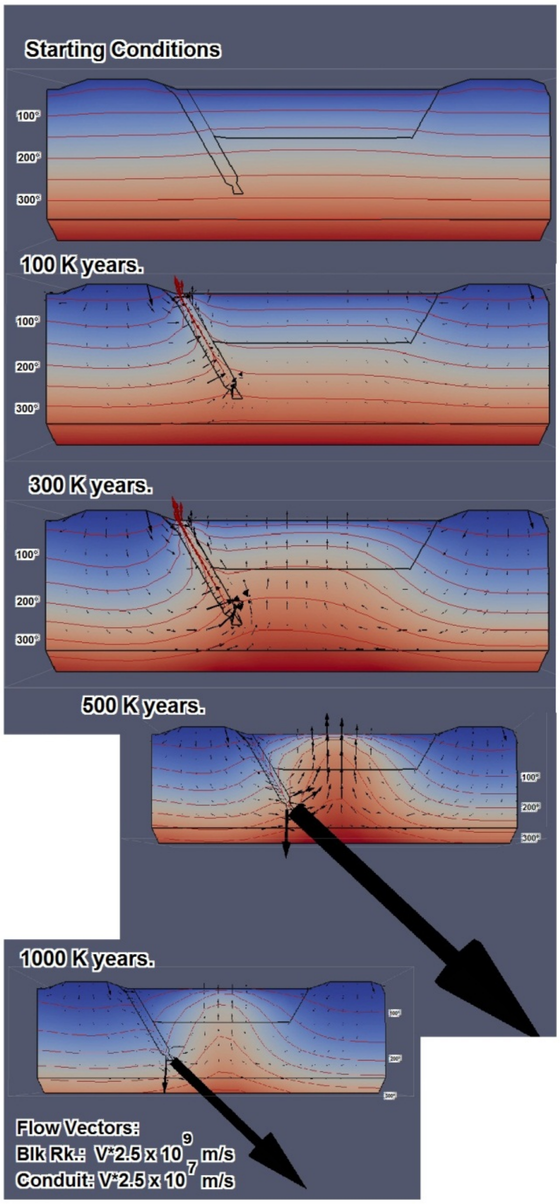



Figure 4. Cross sectional views of Concept 1, $10^{-16}$ bulk rock permeability model.

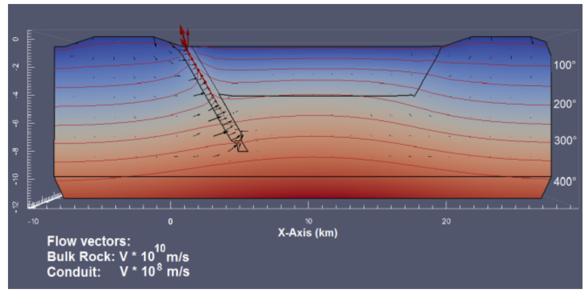



Figure 5. Cross sectional view of Concept 1 - $10^{-17}$ bulk rock permeability model at 4.5 ma.

In all Concept 1 models, inflow from the top of the conduit becomes a significant source of fluids as the system evolves. (Figure 6 shows this for the bulk rock k = $10^{-17}$ $m^2$ model.) While there is little field evidence for such flow, it is a useful indication of the potential importance of inflow along the fault. Concept 2 adds such along-strike inflow to the system.

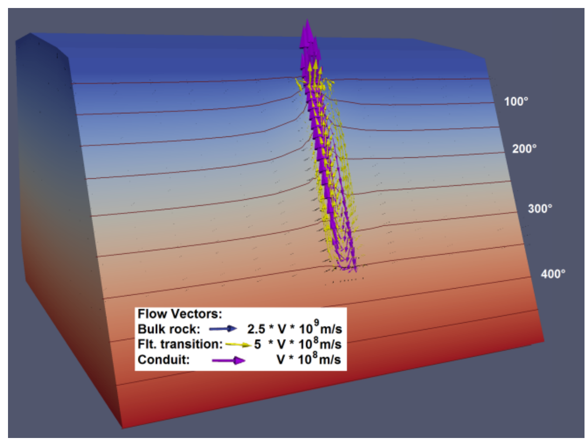
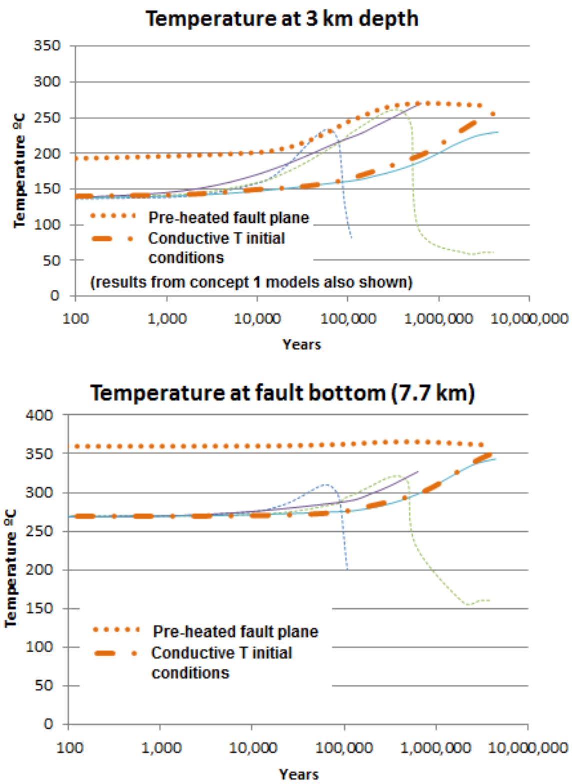



Figure 6. Fault view of Concept 1, $10^{-17}$ $m^2$ bulk rock permeability model at 4.5 ma.

## Results for Concept 2 models

Figures 7a and 7b are plots of temperatures at 3 km depth and at the bottom of the fault conduit over time for Concept 2 pre-heated and conductive T initial conditions.




Figures 7a, 7b. a) temperatures in fault conduit at 3 km depth and b) temperatures at bottom of fault conduit for Concept 2 models.

Temperatures at 3 km depth for the pre-heated model approach 270°C after ~400ka (i.e. matching observed temperatures at Dixie Valley). This model was not run beyond 5 ma, but it appears although the fault conduit may cool off over time, the overall system will not.

Temperatures for the non-preheated model may reach similar temperatures as the pre-heated model but take significantly longer than 5ma to do this.

Fault views of Concept 2 models show significant flow from the fault plane to the fault conduit. Over time (too much time for B&R systems), the non-preheated system is very similar to the pre-heated system (Figures 8a, 8b).

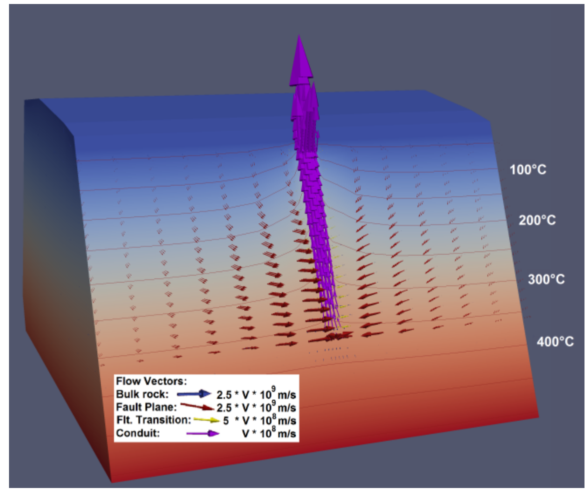



Figure 8a. Fault view of pre-heated concept 2 model at 800 ka.

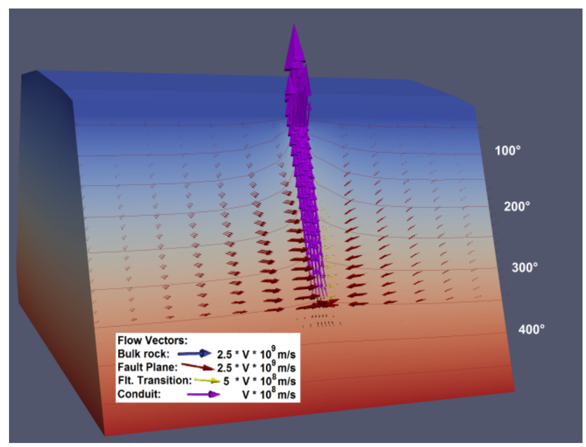



Figure 8b. Fault view of Concept 2 non-preheated (conductive T initial conditions) at 5 ma.

**High conduit permeability models.**

Figures 9a and 9b are plots of temperatures at 3km depth and at the bottom of the fault conduit over time for a high permeability (k = $10^{-13}$ m$^2$) conduit. These models used a bulk rock of k = $10^{-17}$ m$^2$. Three models were tested: (1) using Concept 1 configuration (low permeability fault plane outside of conduit); (2) using Concept 2 configuration (w/intermediate k=$10^{-16}$ m$^2$ fault plane) with conductive T initial conditions; and (3) Concept 2 with pre-heated initial T.

All of these models show a thermal "pulse" by 2 ka (consistent with field evidence from Dixie Valley), but Model 3 results were the most dramatic—reaching a maximum or 295° in 725 years. Figures 10a, 10b, and 10c show the fault view for the maximum temperatures reached by these models. Note that the flow vectors for the fault conduit (purple) in these views are scaled by 0.1 compared to Figures 6, 8a, and 8b.

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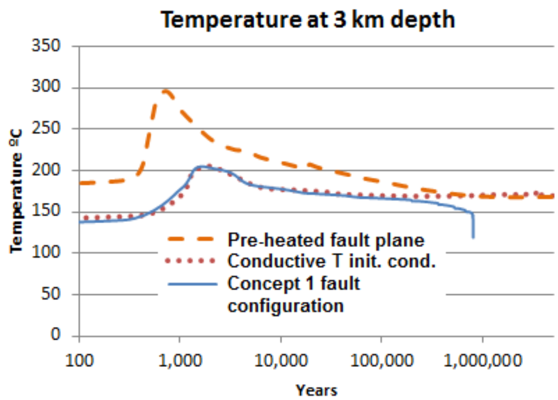
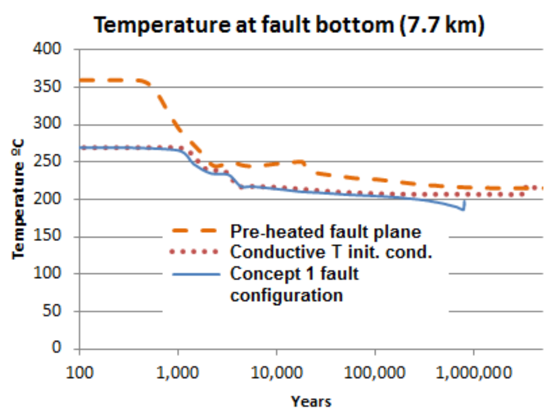



Figures 9. (a) temperatures in fault conduit at 3 km depth; and (b) temperatures at bottom of fault conduit for conduit $k=10^{-13} m^2$ models.

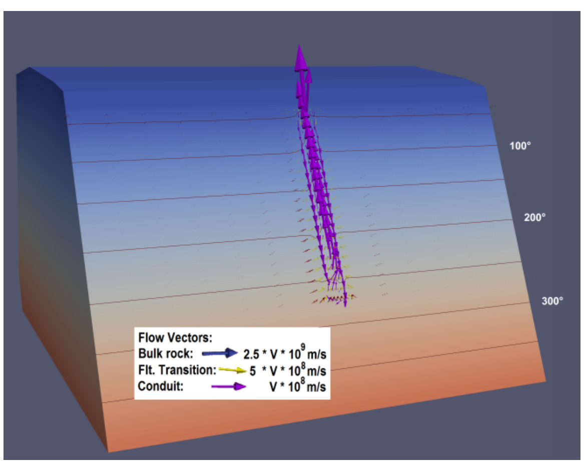



Figure 10a. Fault view of high permeability conduit Model 1 (no intermediate fault plane permeability) at 2 ka.

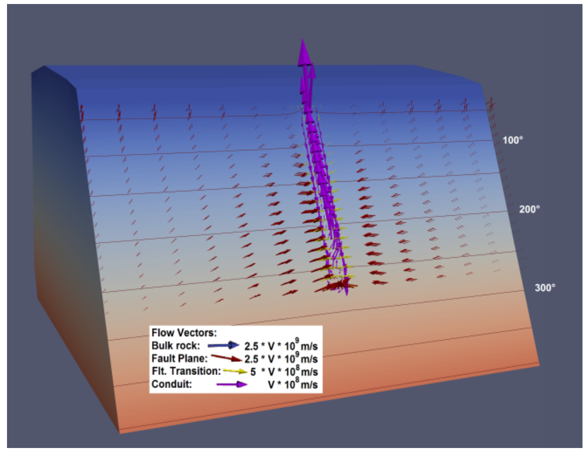



Figure 10b. Fault view of high permeability conduit Model 2 (fault plane $k = 10^{-16}$ $m^2$, conductive T initial conditions) at 1.5 ka.

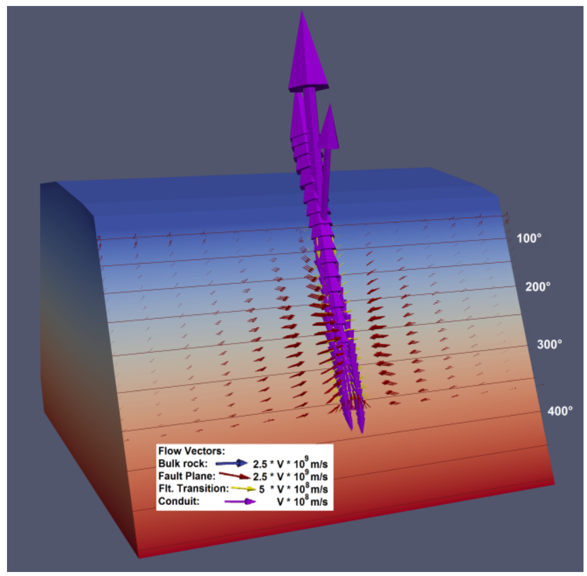
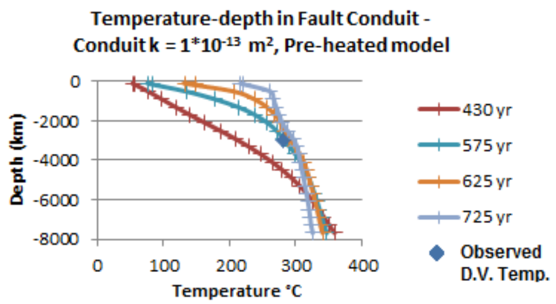
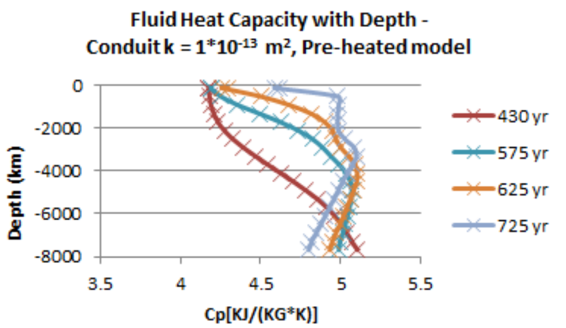



Figure 10c. Fault view of high permeability conduit Model 3 (fault plane $k = 10^{-16}$ $m^2$, pre-heated initial conditions) at 725 yr.

The extreme thermal pulse seen in Model 3 may be enhanced by fluid properties (e.g., buoyancy and heat capacity) that significantly increase as temperature and pressure approach the "critical" point water. Figures 11a and 11b show the temperature and heat capacity of upflowing fluids in the fault conduit. The equation of state, EOS1sc, used for these models accurately models these properties (Brikowski, 2001).




Figures 11a, 11b. Temperature and fluid heat capacity with depth in center of fault conduit for high permeability conduit—Model 3 (pre-heated with intermediate fault plane).

## DISCUSSION AND CONCLUSION

Results from Concept 1 models are quite similar to those of McKenna (2004), at least for high permeability (> $5\times10^{-17}$ $m^2$) models. In these systems, a transient thermal "high" is seen at 50–300 ka, and the entire system eventually cools due to convection (or perhaps due to downflow of cool fluids in the fault conduit). For systems with k < $5\times10^{-17}$ $m^2$, they reach steady-state thermal equilibrium.

The problem with these models is that deep rock permeability >$5\times10^{-17}$ $m^2$ seems unrealistic, considering lithostatic stress at several-kilometer depths, as does the cooling of the model over time. Systems with k < $5\times10^{-17}$ $m^2$ did not allow sufficient convective heat flow to match temperatures seen in Dixie Valley.

Results of Concept 2 models are a somewhat better match to observations, and do not require uncomfortably high permeability at depth to do this. In addition, the temporal response (at least for the pre-heated model) may be more realistic.

High permeability (k = $10^{-13}$ $m^2$) conduit models with moderate along-strike inflow, particularly when preheated, provide the most satisfactory match with current conditions and geologic evidence (temporal correlation of sinter and seismic events) at Dixie Valley. All of the high permeability conduit models show a thermal "pulse" within 2000 years of opening up the fault conduit. This may help explain the origin of these geothermal features in these systems. Enhanced flow from fluid properties of water approaching the critical point is also beginning to occur in Model 3.

Understanding geothermal systems in the B&R province probably involves a combination of several factors. Quasi-3D flow (diffuse recharge into elongated fault zone), "pre-heating" of the fault zone, and enhanced heat transport under semi-optimal fluid conditions may all play a role in the development of these systems.

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